

Dark matter conversion as a source of boost factor for explaining the cosmic ray positron and electron excesses

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Abstract. In interacting multi-component dark matter (DM) models, if the DM components are nearly degenerate in mass and the interactions between them are strong enough, the relatively heavy DM components can be converted into lighter ones at late time after the thermal decoupling. Consequently, the relic density of the lightest DM component can be considerably enhanced at late time. This may contribute to an alternative source of boost factor required to explain the positron and electron excesses reported by the recent DM indirect search experiments such as PAMELA, Fermi-LAT and HESS etc..

In the recent years, a number of experiments such as PAMELA [1], ATIC [2], Fermi-LAT [3] and HESS [4] etc. have reported excesses in the high energy spectrum of cosmic-ray positrons and electrons over the backgrounds estimated from the standard astrophysics, which may be interpreted as indirect signals of the annihilation or decay of dark matter (DM) in the Galactic halo. If the DM particles are thermal relics such as the weakly interacting massive particles (WIMPs), the thermally averaged product of their annihilation cross section with the relative velocity at the time of thermal freeze out is typically $\langle\sigma v\rangle_F \simeq 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$. The positron or electron flux produced by the DM annihilation can be parametrized by

$$\Phi_e = B \bar{N}_e \frac{\rho_0^2 \langle\sigma v\rangle_F}{m_D^2}, \quad (1)$$

where ρ_0 is the smooth local halo DM energy density estimated from astrophysics, \bar{N}_e is the averaged electron number produced per DM annihilation which depends on DM models and parameters in the models for the propagation of cosmic ray particles, and m_D is the mass of the DM particle. The boost factor B is defined as $B \equiv (\rho/\rho_0)^2 \langle\sigma v\rangle / \langle\sigma v\rangle_F$ with ρ the true local DM density and $\langle\sigma v\rangle$ the DM annihilation cross section multiplied by the relative velocity and averaged over the DM velocity distribution today. Both the PAMELA and Fermi-LAT results indicate that a large boost factor is needed [5, 6]. For a typical DM mass of $\sim 1(1.6)$ TeV the required boost factor is $B \sim 500(1000)$ for DM annihilating directly into $\mu^+\mu^-$ and ρ fixed at $\rho_0 = 0.3 \text{ GeV} \cdot \text{cm}^{-3}$ [6].

A large boost factor may arise from the non-uniformity of the DM distribution in the halo. The N-body simulations show, however, that the local clumps of dark matter density are unlikely to contribute to a large enough ρ/ρ_0 [7, 8]. An other possibility of enhancing the boost factor is that the DM annihilation cross section may be velocity-dependent which grows at lower velocities. The DM annihilation cross section today may be much larger than that at the time of thermal freeze out, and thus is not constrained by the DM relic density. Some enhancement mechanisms have been proposed along this line, such as the Sommerfeld enhancement [9–17]. In some non-thermal DM scenarios, the number density of the DM particle can be enhanced by the out of equilibrium decay of some heavier unstable particles if the DM particle is among the decay products of the decaying particle [18, 19]. The decay of the unstable particle must take place at very late time. Otherwise the DM particles with the enhanced number density will annihilate into the Standard Model (SM) particles again, which washes out the enhancement effect.

In this talk, we discuss an alternative origin of the boost factor arising from the late time dark matter conversion processes, which requires neither the velocity-dependent annihilation cross section nor the decay of unstable particles [20]. We show that in the scenarios of interacting multi-component DM, the interactions among the DM components may convert the heavier DM components into the lighter ones, which is not sensitive to the details of the conversion interactions. If the interactions are strong enough and the DM components are nearly degenerate in mass, the conversion can enhance the number density of the lighter DM components at late time after the thermal decoupling. Eventually, the whole DM today in the Universe may consist of only the lightest DM component with enhanced number density, which leads to a large boost factor. The scenarios of multi-component DM have been discussed previously in Refs. [21–30]. Note however that the models with simply mixed non-interacting multi-component DM cannot generate large boost factors.

Let us consider a generic model in which the whole cold DM contains N components χ_i ($i = 1, \dots, N$), with masses m_i and internal degrees of freedom g_i respectively. The DM components are labeled such that $m_i < m_j$ for $i < j$, thus χ_1 is the lightest DM particle. We are interested in the case that χ_i are nearly degenerate in mass, namely the relative mass differences between χ_i and χ_1 satisfy $\varepsilon_i \equiv (m_i - m_1)/m_1 \ll 1$. In this case, we shall show that the interactions between the DM components lead to the DM conversion. The thermal evolution of the DM number density normalized to the entropy density $Y_i \equiv n_i/s$ with respect to the rescaled temperature $x \equiv m_1/T$ is governed by the following Boltzmann equation

$$\frac{dY_i(x)}{dx} = -\frac{\lambda}{x^2} \left[\langle \sigma_i v \rangle (Y_i^2 - Y_{ieq}^2) - \sum_j \langle \sigma_{ij} v \rangle (Y_i^2 - r_{ij}^2 Y_j^2) \right], \quad (2)$$

where $\lambda \equiv xs/H(T)$ is a combination of x , the entropy density s and the Hubble parameter $H(T)$ as a function of temperature T . $Y_{ieq} \simeq (g_i/s)[m_i T/(2\pi)]^{3/2} \exp(-\varepsilon_i x)$ is the equilibrium number density normalized to entropy density for non-relativistic particles. $\langle \sigma_i v \rangle$ are the thermally averaged cross sections multiplied by the DM relative velocity for the process $\chi_i \chi_i \rightarrow XX'$ with XX' standing for the light SM particles which are in thermal equilibrium, and $\langle \sigma_{ij} v \rangle$ are the ones for the DM conversion process $\chi_i \chi_i \rightarrow \chi_j \chi_j$. The quantity

$$r_{ij}(x) \equiv \frac{Y_{ieq}(x)}{Y_{jeq}(x)} = \left(\frac{g_i}{g_j} \right) \left(\frac{m_i}{m_j} \right)^{3/2} \exp[-(\varepsilon_i - \varepsilon_j)x] \quad (3)$$

is the ratio between the two equilibrium number density functions for components i and j . In Eq. (2) we have assumed kinetic equilibrium. The first term in the r.h.s. of Eq.(2) describes the

change of number density of χ_i due to the annihilation into the SM particles, and the second term describes the change due to the conversion to other DM components.

In the case that the cross section of the conversion process $\langle\sigma_{ij}v\rangle$ is large enough, the DM particle χ_i can be kept in thermal equilibrium with χ_j for a long time after both χ_i and χ_j have decoupled from the thermal equilibrium with the SM particles. In this case, the number densities of $\chi_{i,j}$ satisfy a simple relation

$$\frac{Y_i(x)}{Y_j(x)} \approx \frac{Y_{ieq}(x)}{Y_{jeq}(x)} = r_{ij}(x). \quad (4)$$

Even when χ_i is in equilibrium with χ_j the ratio of the number density $Y_i(x)/Y_j(x)$ can be quite different from unity and can vary with temperature. For instance, if $g_i \gg g_j$ and $0 < (\epsilon_i - \epsilon_j) \ll 1$, from Eq. (3) and (4) one obtains $Y_i(x) \gg Y_j(x)$ at the early time when $(\epsilon_i - \epsilon_j)x \ll 1$. However, at the late time when $(\epsilon_i - \epsilon_j)x \gg 1$, one gets $Y_i(x) \ll Y_j(x)$, which is simply due to the Boltzmann suppression factor $\exp[-(\epsilon_i - \epsilon_j)x]$ in the expression of r_{ij} . Thus the heavier particles can be gradually converted into lighter ones through this temperature-dependent equilibrium between χ_i and χ_j .

An interesting limit to consider is that the rates of DM conversion are large compared with that of the individual DM annihilation into the SM particles, i.e. $\langle\sigma_{ij}v\rangle \gtrsim \langle\sigma_i v\rangle$. In this limit, after both the DM components have decoupled from the thermal equilibrium with the SM particles, which take place at a typical temperature $x = x_{dec} \approx 25$, the strong interactions of conversion will maintain an equilibrium between χ_i and χ_j for a long time until the rate of the conversion cannot compete with the expansion rate of the Universe. Making use of Eq. (4), the evolution of the total density $Y(x) \equiv \sum_{i=1}^N Y_i(x)$ can be written as

$$\frac{dY}{dx} = -\frac{\lambda}{x^2} \langle\sigma_{eff}v\rangle (Y^2 - Y_{eq}^2), \quad (5)$$

where $\langle\sigma_{eff}v\rangle$ is the effective thermally averaged product of DM annihilation cross section and the relative velocity which can be written as

$$\langle\sigma_{eff}v\rangle = \frac{\sum_{i=1}^N w_i g_i^2 (1 + \epsilon_i)^3 \exp(-2\epsilon_i x)}{g_{eff}^2} \langle\sigma_1 v\rangle, \quad (6)$$

where $w_i \equiv \langle\sigma_i v\rangle/\langle\sigma_1 v\rangle$ is the annihilation cross section relative to that of the lightest one. The total equilibrium number density can be written as

$$Y_{eq} \equiv \sum_{i=1}^N Y_{ieq}(x) \approx g_{eff} \left(\frac{m_1 T}{2\pi} \right)^{3/2} \exp(-x), \quad (7)$$

with an effective degrees of freedom $g_{eff} = \sum_i g_i (1 + \epsilon_i)^3 \exp(-\epsilon_i x)$. Note that the conversion terms do not show up explicitly in Eq. (5). Through the conversion processes $\chi_i \chi_i \rightarrow \chi_j \chi_j$ the slightly heavier components will be converted into the lighter ones, because the factor $r_{ij}(x)$ is proportional to $\exp[-(m_i - m_j)/T]$ which suppresses the density of the heavier components at lower temperature. If the conversion cross section is large enough, most of the DM components will be converted into the lightest χ_1 before the interaction of conversion decouples, which may result in a large enhancement of the relic density of χ_1 and leads to a large boost factor.

As an example, let us consider a generic DM model with only two components. For relatively large conversion cross section $u \equiv \langle\sigma_{21}v\rangle/\langle\sigma_1 v\rangle \gtrsim 1$, The effective total cross section is given by $\langle\sigma_{eff}v\rangle = \langle\sigma_1 v\rangle [1 + wg^2 \exp(-2\epsilon x)]/[1 + g \exp(-\epsilon x)]^2$, where $w \equiv w_2$, $g \equiv g_2/g_1$ and $\epsilon \equiv \epsilon_2$.

Because of the x -dependence in $\langle\sigma_{eff}v\rangle$, the thermal evolution of $Y(x)$ differs significantly from that of the standard WIMP. In the case that χ_2 has large degrees of freedom but a small annihilation cross section, namely $g \gg 1$, $w \ll 1$ and $wg^2 \ll 1$, the thermal evolution of the total density Y can be simplified. The thermal evolution of the total number density can be roughly divided into four stages: i) At high temperature region where $3 \lesssim x \ll x_{dec}$, both the DM components are in thermal equilibrium with the SM particles. $Y_i(x)$ must closely track $Y_{ieq}(x)$ which decrease exponentially as x increases. However, since $g \gg 1$ and $\epsilon \ll 1$, the number density of χ_2 is much higher than that of χ_1 , i.e. $Y_2(x) \gg Y_1(x)$. ii) When the temperature goes down and x is close to the decoupling point x_{dec} , both the DM components start to decouple from the thermal equilibrium. In the region $x_{dec} \lesssim x \ll 1/\epsilon$, $\langle\sigma_{eff}v\rangle$ is nearly a constant and $\langle\sigma_{eff}v\rangle \approx \langle\sigma_1v\rangle/(1+g)^2 \ll \langle\sigma_1v\rangle$, the total density $Y(x)$ behaves just like that of an ordinary WIMP which converges quickly to $Y(x) \approx x_{dec}/(\lambda\langle\sigma_1v\rangle)$. iii) As x continues growing, the suppression factor $\exp(-\epsilon x)$ in $\langle\sigma_{eff}v\rangle$ becomes relevant. The value of $\langle\sigma_{eff}v\rangle$ grows rapidly especially after x reaches the point $\epsilon x \approx \mathcal{O}(1)$, which leads to the further reduction of $Y(x)$. In this stage, although both $\chi_{1,2}$ have decoupled from the thermal equilibrium with the SM particles. The strong conversion interaction $\chi_2\chi_2 \leftrightarrow \chi_1\chi_1$ maintains an equilibrium between the two DM components. According to Eq. (4), the relative number density $Y_2(x)/Y_1(x)$ decreases with x increasing, which corresponds to the conversion from the heavier DM component into the lighter one. At the point $x_c = (1/\epsilon)\ln g$ one has $Y_2(x) \approx Y_1(x)$. For the region $x > x_{dec}$ and x is not close to x_c , because of $Y_{eq}(x) \ll Y(x)$ and $g\exp(-\epsilon x) \gg 1$, the total number density can be analytically integrated out, and $Y(x)$ in this region can be approximated by

$$Y(x) \approx \frac{g^2 x_{dec}}{\lambda\langle\sigma_1v\rangle} \left[1 + \left(\frac{x_{dec}}{x} \right) \frac{\exp(2\epsilon x)}{2\epsilon x} \right]^{-1}. \quad (8)$$

iv) When x becomes very large $\epsilon x \gg \mathcal{O}(1)$, $\langle\sigma_{eff}v\rangle$ quickly approaches $\langle\sigma_1v\rangle$, and becomes independent of x again. The evolution of $Y(x)$ in this region can be obtained by a simple integration as it was done in the stage ii). The solution of $Y(x)$ shows a second decoupling. Finally when the conversion rate cannot compete with the expansion rate of the Universe at some point x_F corresponding to $sY_2\langle\sigma_{21}v\rangle/H \approx 1$, both $Y_1(x)$ and $Y_2(x)$ remain unchanged as relics. The whole DM can be dominated by χ_1 if the conversion is efficient enough.

By matching the analytic solutions of $Y(x)$ in different regions near the points x_{dec} and x_c , and requiring that the final total relic density is equivalent to the observed $\Omega_{CDM}h^2 \approx 0.11$, we obtain the following approximate expression of the boost factor

$$B \approx g^2 \left[1 + \left(\frac{x_{dec}}{x_c} \right) \left(\frac{\exp(2\epsilon x_c)}{2\epsilon x_c} + g^2 \right) \right]^{-1}. \quad (9)$$

As expected, the enhancement essentially comes from the conversion of the degrees of freedom. Thus the maximum enhancement is g^2 . The two terms in the r.h.s of the above equation correspond to the reduction of $Y(x)$ during the late time conversion stages. For large enough g , the boost factor can be approximated by $B \approx g^2/(1 + \epsilon g^2 x_{dec}/\ln g)$. In order to have a large boost factor, a small $\epsilon \ll \ln g/(g^2 x_{dec})$ is also required. As shown in Eq. (9) the boost factor is not sensitive to the exact values of the cross sections as long as the conditions $w \ll 1$ and $u \gg 1$ are satisfied.

We numerically calculate the thermal evolution of $Y_i(x)$ and the boost factor without using approximations for a generic two-component DM model. The results for $w = 10^{-4}$, $u = 10$ and $\epsilon = 2 \times 10^{-4}$ is shown in Fig. 1. The value of $\langle\sigma_2v\rangle$ is adjusted such that the final total DM relic abundance is always equal to the observed value $\Omega_{CDM}h^2$. The mass of the light DM particle is set to $m_1 = 1$ TeV. For an illustration the ratio between the internal degrees of freedom is set to be large $g = 60$. From the figure, the four stages of the thermal evolution of $Y(x)$ as well as the

crossing point can be clearly seen. The crossing point at $x = x_c \approx 2 \times 10^{-4}$ indicates the time when the number density of χ_1 start to surpass that of χ_2 and eventually dominant the whole DM relic density. In this parameter set a large boost factor $B \approx \langle \sigma_1 v \rangle / \langle \sigma v \rangle_F \approx 585$ is obtained which is in a remarkable agreement with Eq. (9) with error less than $\sim 5\%$. For a comparison, in Fig. 1 we also show the cases without conversions.

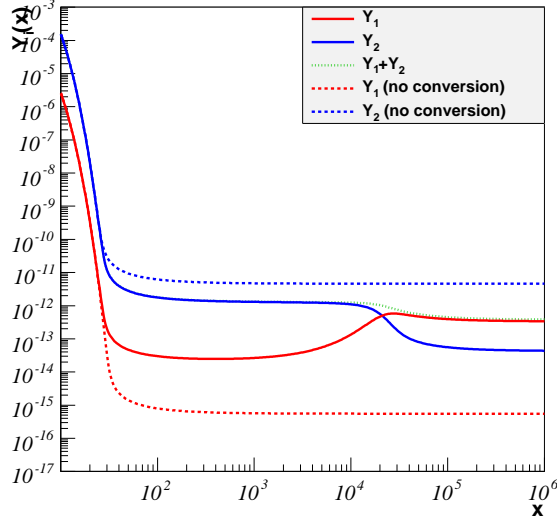


Figure 1. Thermal evolution of the number densities $Y_1(x)$ (red solid) and $Y_2(x)$ (blue solid) with respect to x . The solid (dashed) curves correspond to the case with (without) DM conversions. The green dotted curve corresponds to the sum of Y_1 and Y_2 , for parameters $g = 60$, $m_1 = 1\text{TeV}$, $\varepsilon = 2 \times 10^{-4}$, $w = 10^{-4}$ and $u = 10$ respectively.

The whole DM in the universe necessarily contains multiple components, as the lightest active neutrino already contributes to a small fraction of the DM relic density. It is easy to construct models with more stable neutrinos or neutrinos with lifetime longer than that of the universe. For instance, in fourth generation models with right-handed neutrinos, extra stable neutrinos may be the keV scale sterile neutrinos and the heavy Majorana neutrinos which are stable due to additional symmetries [31]. For models with multiple DM components, it is possible that there exists interactions among the DM components which may lead to the conversions among them. In this talk we consider a simple interacting two-component DM model by adding to the standard model (SM) with two SM gauge singlet fermionic DM particles $\chi_{1,2}$. The particles $\chi_{1,2}$ are charged under a local $U(1)$ symmetry which is broken spontaneously by the vacuum expectation value (VEV) of a scalar field ϕ . The corresponding massive gauge boson is denoted by A which may cause the reaction $\bar{\chi}_2 \chi_2 \leftrightarrow \bar{\chi}_1 \chi_1$. The stability of $\chi_{1,2}$ is protected by two different global $U(1)$ number symmetries. An SM gauge singlet pseudo-scalar η is introduced as a messenger field which couples to both the dark sector and the SM sector. In order to have the leptophilic nature of DM annihilation, we also introduce an SM $SU(2)_L$ triplet field Δ with the SM quantum number $(1, 3, 1)$ and flavor contents $\Delta = (\delta^{++}, \delta^+, \delta^0)$. The triplet carries the quantum number $B - L = 2$ such that it can couple to the SM left-handed leptons ℓ_L through Yukawa interactions $\bar{\ell}_L^c \Delta \ell_L$, but cannot couple to quarks directly. The VEV of the triplet has to be very small around eV scale, which is required by the smallness of the neutrino masses. As a consequence, the couplings between one triplet and two SM gauge bosons such as $\delta^{\pm\pm} W^\mp W^\mp$, $\delta^\pm W^\mp Z^0$ and $\delta^0 Z^0 Z^0$ are strongly suppressed as they are all proportional to the VEV of the

triplet, which makes it difficult for the triplet to decay even indirectly into quarks through SM gauge bosons [32–37]. If η has a stronger coupling to Δ than that to the SM Higgs boson H and ϕ then the annihilation products of the dark matter particles $\chi_{1,2}$ will be mostly leptons.

The Lagrangian of the model can be written as $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_1$. The new interactions in \mathcal{L}_1 which are relevant to the DM annihilation and conversion are given by

$$\begin{aligned} \mathcal{L}_1 \supset & \bar{\chi}_i(i\not{D} - m_i)\chi_i + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi \\ & + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}m_\eta^2\eta^2 - y_i\bar{\chi}_i i\gamma_5\eta\chi_i - y_\ell\bar{\ell}_L^c\Delta\ell_L + \text{h.c} \\ & - (\mu\eta + \xi\eta^2) \left[\text{Tr}(\Delta^\dagger\Delta) + \kappa(H^\dagger H) + \zeta(\phi^\dagger\phi) \right], \quad (i = 1, 2) \end{aligned} \quad (10)$$

Note that ϕ and η do not directly couple to the SM fermions. After the spontaneous symmetry breaking in $V(\phi)$, the scalar ϕ obtains a nonzero VEV $\langle\phi\rangle = v_\phi/\sqrt{2}$ which generates the mass of the gauge boson $m_A = g_A v_\phi$. At the tree level, the three components of the triplet δ^{++}, δ^+ and δ^0 are degenerate in mass, i.e. $m_{\delta^{++}} = m_{\delta^+} = m_{\delta^0} \equiv m_\Delta$.

We assume that χ_2 has large internal degrees of freedom relative to that of χ_1 , i.e., $g_2 \gg g_1$, which can be realized if χ_2 belongs to a multiplet of the product of some global nonabelian groups. For instance $g_2 = 4\tilde{g}_2$ with $\tilde{g}_2 = 16, 8$, and 4 if it belongs to the spinor representation of a single group of $SO(8)$, $SO(6)$ and $SO(4)$ respectively. When χ_2 belongs to a representation of the product of these groups, its internal degrees of freedom can be very large.

At the early time when the temperature of the Universe is high enough, the triplet Δ can be kept in thermal equilibrium with SM particles through the SM gauge interactions. The DM particles χ_i are in thermal equilibrium by annihilating into the triplet through the intermediate particle η . The annihilation $\bar{\chi}_2\chi_2 \rightarrow \eta^* \rightarrow \delta^{\pm\pm}\delta^{\mp\mp}, \delta^{\pm}\delta^{\mp}, \delta^0\delta^{0*}$ is an s -wave process which is the dominant contribution. The ratio of the two annihilation cross sections is $w = (y_2/y_1)^2(g_1/g_2)$. It is easy to get a very small w provided that $y_2 \ll y_1$ and $g_1 \ll g_2$. In order to have a large enough $\langle\sigma_1 v\rangle \gg \langle\sigma v\rangle_F$ the product of the coupling constants $y_1\mu$ must be large enough, or the squared mass of η is close to s . The cross section of the conversion process $\bar{\chi}_2\chi_2 \rightarrow A^* \rightarrow \bar{\chi}_1\chi_1$ is suppressed by g_1/g_2 and also the phase space factor $\sqrt{1 - 4m_1^2/s}$ when s is close to $4m_2^2$ at the very late time of the thermal evolution. However, the cross section can be greatly enhanced if m_A is close to a resonance when the relation $s \simeq m_A^2$ is satisfied. In the numerical calculations, we find that for the following selected parameters: $m_1 = 1\text{TeV}$, $\epsilon = 1 \times 10^{-4}$, $g_1 = 1$, $g_2 = 60$, $m_\Delta = 500\text{ GeV}$, $m_\eta = 1.5\text{ TeV}$, $m_A = 2.02\text{ TeV}$, $y_1 = 3$, $y_2 = 0.07$, $\mu/m_1 = 3$, and $g_A = 2.5$, the following ratio of the cross section can be obtained

$$w \simeq 1 \times 10^{-5}, \quad u \simeq 0.5, \quad \text{and} \quad \langle\sigma_1 v\rangle/\langle\sigma v\rangle_F \simeq 500.$$

In this parameter set the relative mass difference between m_A and $2m_2$ is around 1%. The corresponding boost factor is $B \sim 500$, which is large enough to account for the PAMELA data for the dark matter mass around TeV.

In summary, We have considered an alternative mechanism for obtaining boost factors from DM conversions which does not require the velocity-dependent annihilation cross section or the decay of unstable particles. We have shown that if the whole DM is composed of multiple components, the relic density of each DM component may not necessarily be inversely proportional to its own annihilation cross section. We demonstrate the possibility that the number density of the lightest DM component can get enhanced in late time through DM conversion processes, and finally dominates the whole relic abundance, which corresponds to a boost factor needed to explain the excesses in cosmic-ray positron and electrons reported by the recent experiments.

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